Optica Applicata, Vol. XXVIII, No. 3, 1998

Investigations of cavity losses in diode pumped lasers*

JAN K. JABCZYŃSKI, KRZYSZTOF KOPCZYŃSKI, PIOTR MARCINIAK

Institute of Optoelectronics, Military University of Technology, ul. Kaliskiego 2, 01–489 Warszawa, Poland.

Two methods of losses measurements: Findlay–Clay's method and relaxation frequency method were verified for two types of diode pumped lasers. In the case of Nd:YAG laser with changeable output coupler, the results obtained for both methods were in good agreement. However, there was observed a contradiction between the relatively high losses (about 10% for transmission losses of 5%) and very high slope efficiency (~50%) of this laser. The measurements of cavity losses via relaxation method were carried out for several types of microlasers made of Nd:YAG, Ng:GGG, Nd:YAP crystals and Nd:phosphate glass. There were obtained total losses (including transmission ones) on the range from 7% to 30%.

1. Introduction

Diode pumped lasers (DPL's), due to the narrow spectrum of pump radiation well matched to absorption peak of active medium and good overlapping of pump caustics and fundamental mode of cavity, can be very efficient sources of coherent radiation [1], [2]. They emit, as a rule, diffraction limited beams; moreover, a single frequency regime of work is a frequent and easy to achieve option [3], [4]. High slope and optical efficiencies, low thresholds and possibilities of mass production enabled construction of reliable and cheap DPL's for several metrological applications.

To construct efficient DPL high gain and low cavity losses should be achieved simultaneously. Both parameters depend on geometry of pump and laser modes as well as physical properties of active medium and quality of laser elements. The procedure of Findlay–Clay [5] (FCM) enables determination of both parameters from measurements of thresholds for several transmission losses. In this case, it is assumed that threshold pump is proportional to total logarithmic losses of cavity. This procedure can be applied in an early stage of construction and has limited application only for lasers in which the changing of output mirror is possible and laser mode shape and losses do not depend on pump power. Such conditions are not valid in numerous diode pumped lasers, *e.g.*, monolithic microchips. The alternative method for investigating losses consists in measurements of frequency of relaxation oscillation (RFM) [6], [7]. In this case, the frequency of relaxation oscillation is

---

* This paper was presented at the International Conference on Optoelectronic Metrology OM'98, held in Łańcut (Poland), on September 28–30, 1998.

measured as a function of pump power over threshold. Making use of this relation one can determine decay time of photon in the cavity and cavity losses.

The aim of this paper is verification of these two methods for two types of diode pumped lasers, namely: end pumped laser with flat output mirror and microchip. The energetic characteristics and cavity losses using both FCM and RFM procedures were measured for the first type of laser (Sec. 3) For the second one, losses were measured applying the RFM procedure for several microchips (Sec. 4). The results of measurements are discussed in the last section.

2. Experimental set-up

The experimental set-up (see Fig. 1) consisted of diode pumped laser controlled by laser diode driver, the power meter for measurement of energetic characteristics and photo detector with high pass preamplifier for recording intensity noises of generation in the range of 10 kHz – 10 MHz.

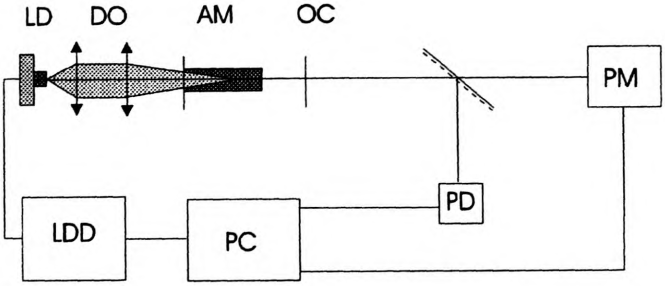

Fig. 1. Scheme of laboratory set-up: LD – pumping laser diode, DO – diode beam forming optics, AM – active medium, OC – changeable output coupler (only for laser type I), PD – photo detector with high pass preamplifier, PM – power meter, PC – 486'PC computer, LDD – laser diode driver

The laser diode driver enabled stabilization of pump current with accuracy better than 1% and control of TEC temperature of diode laser with accuracy better than 1 K. In the case of energetic characteristics measurements both power supply and power meter output were controlled by data acquisition card PCL 812 PG. In measurement of relaxation oscillations, CS1012 oscilloscope card with 20 MHz sampling rate and home made softwate [8] were applied.

Two types of DPL's were investigated:

1. In the first type of laser 2W laser diode LDT 27004 with emitting area 200×1 μm^2 was used as a pump source. The pump beam was transformed by divergence equalising system into astigmatic caustics of the size 250×40 μm^2 and divergence half angle of about 50 mrad. The laser cavity consisted of Nd:YAG rod with rear mirror deposited on its left facet and flat external output coupler placed at several distances from the rod.

2. In the second type of laser, as a pump source the 1W fiber coupled diode SDL 2362 with 50 μm core diameter and 0.4 NA was used. The pump beam after pass-

ing through relay system with 2 × magnification formed caustics with 130 μm waist diameter and 230 mrad half angle of divergence.

In both types of lasers, the shape of laser mode is determined by the shape of pump radiation via gain/thermal guiding effects [9]. In the preliminary stage of investigations the pump caustics shapes were measured (see Fig. 2**a**,**b**).

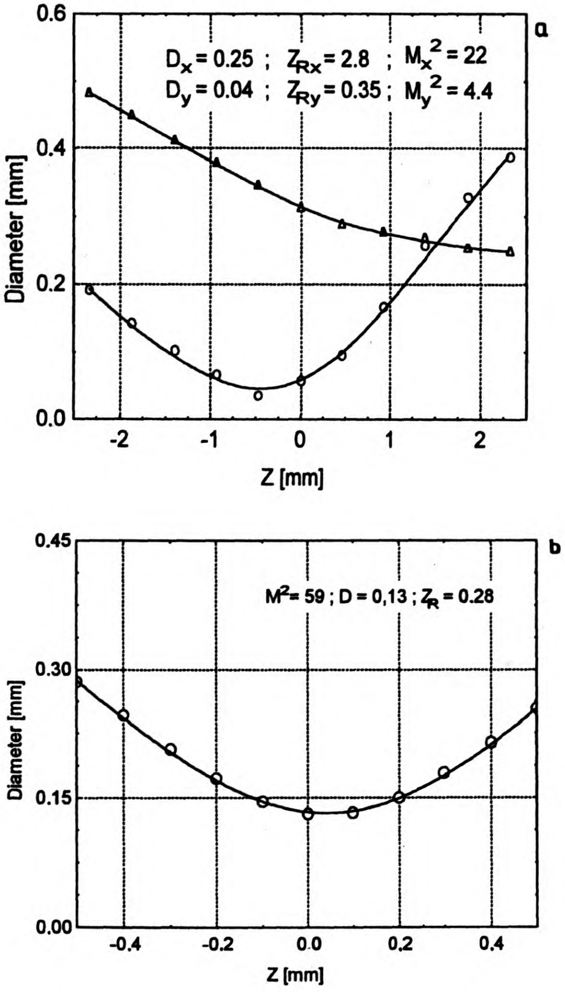

Fig. 2. Beam sizes vs. distance measured in caustics of pump system type I. Triangles denote beam sizes in *x*-plane, circles denote beam sizes in *y*-plane (**a**). Beam diameter vs. distance measured in caustics of pump system type II (**b**)

It was established from calculations that the averaged area with respect to pump absorption [10] was 45000 μm^2 for the first type pump beam and about 30000 μm^2 for the second type of pump. There was observed near TEM$_{00}$ output for the full range of the pump power examined for both types of lasers. Measurements of divergence of output beam showed that for the first type of laser the waist diameter was approximately 600 μm and did not change significantly with respect to pump power, whereas the waist diameter of microchip laser decreased with pump power due to thermal/gain guiding effect [9]. However, in both cases, the laser mode had larger size in the active medium than the respective pump sizes.

3. Measurements of cavity losses for the first type of laser

Assuming the fact that for several transmission losses (defined as $-\ln(R)$, where R denotes reflectivity of output coupler) laser beam size is the same at threshold pump P_{thr} and the passive cavity losses L_c do not depend on threshold power the dependence of transmission losses on threshold pump is the following:

$$-\ln(R) = 2\cdot K\cdot P_{\mathrm{thr}} - L_c \tag{1}$$

where K denotes gain per pump power. In this case, the one pass gain $g_0 l$ for a given incident pump power P_{in} is as follows:

$$g_0 l = K\cdot P. \tag{2}$$

There were measured the energetic characteristics (see, *e.g.*, Fig. 3) of laser that consisted of 10 mm length Nd:YAG rod with flat facets and plane output coupler located at a given distance from the rod.

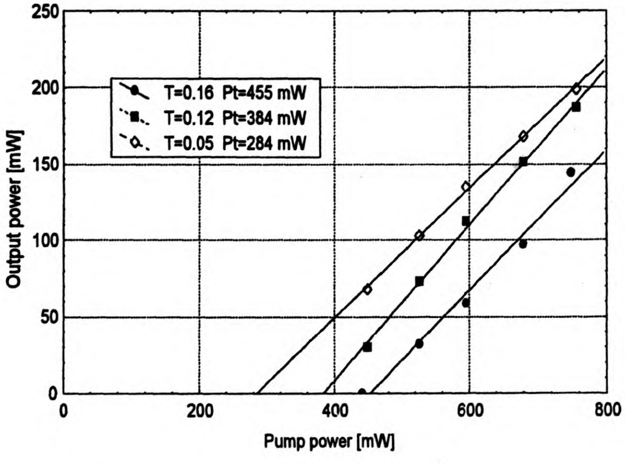

Fig. 3. Output characteristics of laser type I of 27.5 mm geometrical length

The threshold pumps for a given OC were determined from linear regression of energetic characteristics. Measurements of output characteristics were carried out for a few output couplers, and further cavity losses and gain were calculated according to FCM procedure (formulae (1), (2), see Fig. 4).

The second method of losses investigations, *i.e.*, the RFM method consisted in measurements of medium frequency of intensity noises averaged with respect to noise spectrum [8]. For the low excess of pump power over threshold there is observed

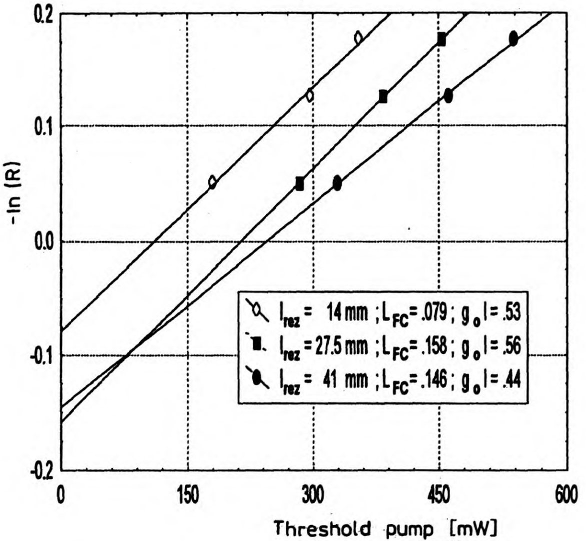

Fig. 4. Transmission losses vs. threshold powers for several resonator lengths l_{rez}

a stable relaxation peak in intensity spectrum whose frequency f_{rel} is proportional to the square root of pump power (see details in [6], [7]) as follows:

$$f_{rel} = \frac{1}{2\pi}\sqrt{\frac{r}{\tau_c \tau_f}} \tag{3}$$

where r denotes pumping parameter,

$$r = \frac{P}{P_{thr}} - 1, \tag{4}$$

P – pump power, P_{thr} – threshold power, τ_f – fluorescent time of relaxation of crystal upper level, and τ_c – decay time of photon in the cavity. On the other hand, the τ_c is related with cavity parameters in the following way:

$$\frac{1}{\tau_c} = -\frac{c}{2l_{opt}}[\ln(R) + L_c] \tag{5}$$

where c denotes light velocity, l_{opt} – optical length of cavity, R – reflectivity of output coupler (it was assumed that reflectivity of rear mirror deposited on the rod is 1), and L_c denotes the passive logarithmic losses of cavity. All measurements were carried out for Nd:YAG crystal which had 230 μs upper level lifetime. The values of decay time τ_c were determined from linear regression of relation between square of relaxation frequency and pumping parameter r for several pump levels (see Fig. 5).

Passive cavity losses L_c were calculated from formula (4), (see Fig. 5 and Tab. 1). The threshold powers used in calculations of pumping paremeter r were determined from energetic characteristics. Linear correlation coefficients for all data sets were better than 0.995. Error measurements in RFM procedure depends also on ac-

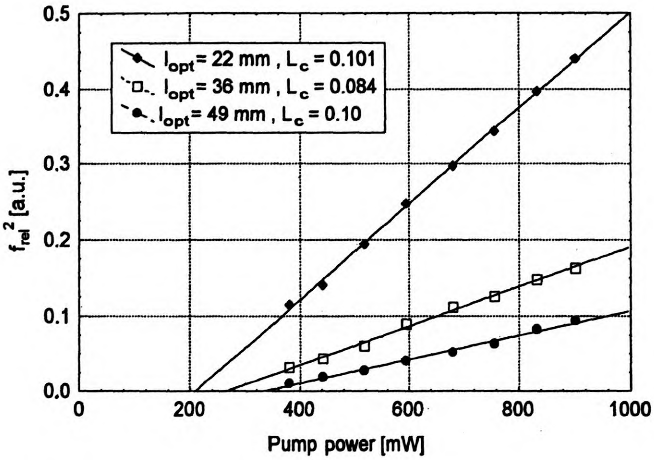

Fig. 5. Square of relaxation frequency as a function of pump power for several optical lengths of cavity: OC transmission was 5%

Table 1. Losses and optical slope efficiencies $\eta_{opt,s1}$ of flat cavity measured by FCM and RFM procedures: L_{FCM} – losses measured by Findlay–Clay method, L_{RFM} – losses measured by relaxation frequency method, l_{rez} – geometrical length of cavity

l_{rez} [mm]	14	22.5	41
$\eta_{opt,s1}$ [%]	45	48	50
L_{FCM} [%]	7.9	15.8	14.6
L_{RFM} [%]	10.1	8.4	10

curacy of threshold, cavity length and upper level lifetime measurements. Thus, we find that uncertainty of losses estimation via relaxation frequency measurements is on the level of 10–20%. As shown in Table 1, there are relatively large differences between results obtained for FCM and RFM methods. Moreover, such big losses are contradictory to very high slope efficiency of laser (about 50%).

4. Measurements of relaxation oscillation frequency of microchip lasers

Similar measurements of cavity losses were carried out for microchip lasers pumped by the second type of pump system. In this case, only the RFM procedure was used. The results of relaxation frequency measurements are shown in Figs. 6 and 7.

Because of the problems with precise determination of transmission losses there were calculated the total cavity losses including transmission of mirrors (see Tab. 2). The correlation coefficients for these sets of data were not so high as in the case of the first type of laser. Moreover, much greater instabilities in output power and noise spectrum were observed for such a type of lasers.

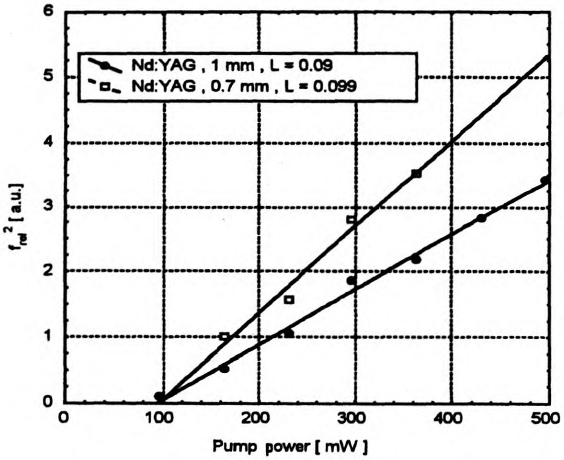

Fig. 6. Square of relaxation frequency vs. pump power for Nd:YAG microchips

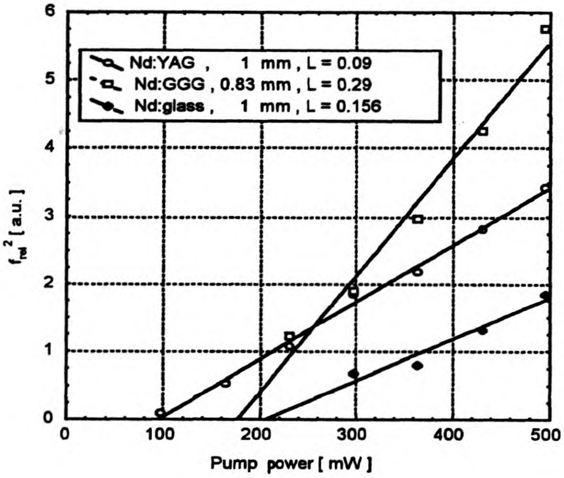

Fig. 7. Square of relaxation frequency vs. pump power for several neodymium microchips

Table 2. Cavity losses (including transmission part $-\ln(R_1 R_2)$) and optical slope efficiencies $\eta_{\mathrm{opt,s1}}$ of several microchips

No.	Active medium	Microchip thickness [mm]	$\eta_{\mathrm{opt,s1}}$ [%]	Losses [%]
1	Nd:YAG	1	18	9
2	Nd:YAG	0.7	18	9.9
3	Nd:GGG	1.01	10	7.6
4	Nd:GGG	0.83	8	29.1
5	Nd:YAP	0.8	5	12.5
6	Nd:glass	1.02	5	15.6

5. Conclusions

There were examined two methods of cavity losses measurements (Findlay–Clay and relaxation oscillation methods) for diode pumped lasers. For relatively long cavity with external output coupler the qualitative agreement between results of these methods was shown. In this case, the laser mode size was not significantly influenced by changes of pump power. Moreover, due to longitudinal multimode output relatively stable output power and spectrum of generation was observed. However, the level of losses (about 10%) was one order higher than expected, taking into account scattering losses on imperfections of bulk and surfaces of active medium. Moreover, such high losses are contradictory to excellent slope efficiency (about 50%) and optimal transmission 5% observed in this laser. Such high losses can be explained by diffraction of laser mode on pump area which was about a quarter of the area of laser mode. This effect due to the gain guiding phenomenon causes the distortion from Gaussian shape of fundamental mode of "hot" cavity (see, *e.g.*, [9], [11]). As a result, the output power does not diminish but the quality of cavity and decay time of photon decrease.

Application of RFM for measurements of microchips losses is much more doubtful. In this case, measured losses are of one order higher than expected, although similar results were obtained in other works [7], [12]. In this case, gain and output transmission are much lower than in the previous case (the ratio of transmission losses to total cavity losses is about 10%), thus the contradiction between the relatively high slope efficiency observed (about 30–40%) and such high losses is much more evident. In the case of single frequency lasers, an additional type of losses occurs [13]. It consists in changes of resonance conditions, induced by pump power, and resulting "detuning" of mode frequency of fluorescence spectrum peak. In such a way gain decreases and this disturbance can be observed as an increase of losses. Thus, the assumption of the losses being independent of the pump power is not valid. Moreover, due to a significant decrease of laser mode area with pump power (typical of microchip lasers) the intensity of photon flux inside cavity is a nonlinear function of pump power, which does not allow application of linear regression analysis of frequency square and pumping parameter r.

The main source of errors in both methods is the uncertainty in threshold measurements. It was shown that 5% changes in threshold can result in more than 20% changes in cavity losses determined from the RFM method. To minimize problems with "detuning" effect the control of generation spectrum should be realized simultaneously with noise spectrum investigations and microchip should be thermally tuned to emission peak for each pump level.

Acknowledgements – This work was supported by the Polish Committee for Scientific Research under the grant PBZ 2183/T1197/10. We would like to thank Dr. W. Żendzian for valuable suggestions and discussion on experiments. Thin film coatings on active media were prepared by Dr. J. Ciosek and Dr. M. Trnka.

References

[1] FAN T. Y., BYER R., IEEE J. Quantum Electron. **24** (1988), 895.
[2] LAPORTA P., BRUSSARD M., IEEE J. Quantum Electron. **27** (1991), 2319.
[3] KANE T. J., BYER R. L., Opt. Lett. **10** (1985), 65.
[4] ZAYHOWSKI J. J., MOORADIAN A., Opt. Lett. **14** (1989), 24.
[5] FINDLAY D., CLAY R. A., Phys. Lett. **20** (1966), 277.
[6] KOECHNER W., [in] *Solid State Laser Engineering*, IV ed., Springer-Verlag, 1995, pp. 106–109.
[7] BEIER B., MEYN J. P., KNAPPE R., BOLLER K. J., HUBER G., WALLENSTEIN R., Appl. Phys. B **58** (1994), 381.
[8] JABCZYŃSKI J., SZCZĘŚNIAK A., Opt. Appl. **25** (1995), 281.
[9] ZAYHOWSKI J. J., OSA Proc. Advanced Solid State Lasers **5** (1991), 713.
[10] JABCZYŃSKI J. K., Opt. Commun, **140** (1997), 1.
[11] LONGHI S., LAPORTA P., J. Opt. Soc. Am. A, **12** (1995), 1511.
[12] MEHENDALE S. C., Appl. Opt. **33** (1994), 8330.
[13] KUBODERA K., OTSUKA K., MIYAZAWA S., Appl. Opt. **18** (1973), 884.

Received July 3, 1998
in revised form September 2, 1998